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DIFFUSE EXTRAGALACTIC BACKGROUND LIGHT VERSUS DEEP GALAXY COUNTS IN THE SUBARU DEEP FIELD: MISSING LIGHT IN THE UNIVERSE?

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ABSTRACT

Deep optical and near-infrared galaxy counts are utilized to estimate the extragalactic background light (EBL) coming from normal galactic light in the universe. Although the slope of number-magnitude relation of the faintest counts is flat enough for the count integration to converge, considerable fraction of EBL from galaxies could still have been missed in deep galaxy surveys because of various selection effects including the cosmological dimming of surface brightness of galaxies. Here we give an estimate of EBL from galaxy counts, in which these selection effects are quantitatively taken into account for the first time, based on reasonable models of galaxy evolution which are consistent with all available data of galaxy counts, size, and redshift distributions. We show that the EBL from galaxies is best resolved into discrete galaxies in the near-infrared bands (J, K) by using the latest data of the Subaru Deep Field; more than 80-90% of EBL from galaxies has been resolved in these bands. Our result indicates that the contribution by missing galaxies cannot account for the discrepancy between the count integration and recent tentative detections of diffuse EBL in the K-band (2.2 μm), and there may be a very diffuse component of EBL which has left no imprints in known galaxy populations.

Subject headings: cosmology: observations — diffuse radiation — galaxies: evolution — galaxies: formation

1. INTRODUCTION

Extragalactic background light (EBL) in the optical and near-infrared (NIR) wavebands is a fundamental quantity for galaxy formation and cosmology, which is believed to be dominated by the integration of all stellar light in the universe (Bond, Carr, & Hogan 1986; Yoshii & Takahara 1988). If all stellar light is emitted from galactic systems, the EBL can be resolved into discrete galaxies by deep galaxy surveys. The deepest image of the universe in the optical bands has been obtained by the Hubble Deep Field (HDF; Williams et al. 1996). The faint-end slopes of the HDF galaxy counts in all the four optical bands (U_{300}, B_{450}, V_{606}, and I_{814}) are flatter than the critical slope index $d(\log N)/(dm) = 0.4$, with which the contribution of galaxies to the EBL is constant against magnitudes. Therefore the extrapolation of the galaxy counts into fainter magnitudes does not significantly increase EBL but converges to a finite EBL flux, and this means that the bulk of EBL from galactic light has already been resolved into discrete galaxies (e.g., Madau & Pozzetti 2000). The situation is the same for the NIR band, although there has been a considerable scatter in the faint-end counts in the K band. In fact, the latest K count data of the Subaru Deep Field (SDF; Maihara et al. 2000) with 350 galaxies down to the 5σ limiting magnitude of $K' = 23.5$ show a very flat slope of $d(\log N)/dm \sim 0.23$ to $K \sim 24$.

These results of faint galaxy counts therefore require that the diffuse EBL in optical and NIR bands should not be different from the count integrations, provided that the ordinary galactic light is the dominant source of the EBL in these bands, as generally believed. However, recent (tentative) detections of diffuse EBL in these bands suggest that the diffuse EBL flux is consistently higher than the count integrations. The measurement of the optical EBL by Bernstein et al. (1999) is higher than the optical count integrations by Madau & Pozzetti (2000) by a factor of $\sim$ 2–4. There are several independent reports for detection of the diffuse EBL at the K band (2.2 μm): $\nu I_\nu = 22.4 \pm 6$ nW m^{-2}sr^{-1} (Gorjian, Wright, & Charly 2000), 20.2 ± 6.3 (Wright 2001), and 29.3 ± 5.4 (Matsumoto et al. 2000), which should be compared with the integration of K counts (~ 8 nW m^{-2}sr^{-1}, Madau & Pozzetti 2000).

It should be noted that this is a comparison between two purely observable quantities, and no theoretical modeling is included. Any theoretical model of galaxy formation cannot reproduce *simultaneously* the counts and EBL, al-

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though it is rather easy to construct a model to explain either of the two. If the discrepancy between the diffuse EBL and count integration is real, it might suggest the existence of very diffuse component which is different from normal galaxies. Before deriving this extraordinary conclusion, however, all possible systematic uncertainties in the above estimates must extensively be checked. One of such systematics is the contribution to EBL by the galaxies missed in deep galaxy surveys. Since galaxies are extended sources, the detectability near the detection limit is not as simple as point sources. Furthermore, the well-known effect of the cosmological dimming of surface brightness [$S \propto (1+z)^{-4}$] should make high-z galaxies very difficult to detect, while such objects may have a significant contribution to EBL. The photometry scheme could also be a problem, because there is considerable uncertainty in the estimate of the magnitude of faint galaxies because of 'growing' the photometry beyond the outer detection isophotes of galaxies.

In spite of this importance, no realistic or quantitative estimate of the contribution to EBL from these missing galaxies has been made so far. The purpose of this Letter is to make such an estimate, using realistic galaxy evolution models which reproduce the local galaxy populations as well as deep counts, size and redshift distributions of the faintest galaxies. We will calculate how much galactic light is missed in current deep surveys taking into account the effects mentioned above, under the observational conditions and detection criteria of HDF for optical bands and those of SDF for NIR bands. Then we will derive our best-guess for the EBL flux coming from normal galaxies.

2. METHOD AND MODEL

The examined systematic effects which could lead to missing of faint galaxies are as follows: (1) apparent size and surface brightness profiles of galaxies where the cosmological dimming is taken into account, (2) dimming of an image by seeing, (3) criteria and completeness of galaxy detections under the observational conditions, and (4) photometric scheme (isophotal magnitude applied consistently).

We estimate the contribution of missing galaxies to EBL as follows. First, we construct a model of galaxy counts which best fits to the observed counts, taking into account all the above selection effects. Then we can calculate the true galaxy counts and EBL flux using the same model without selection effects, and comparison between the true counts and observed counts gives an estimate of contribution by missing galaxies. The general formalism to include the selection effects in calculation of galaxy counts has been given in Yoshii (1993), and we have already analyzed the HDF counts and photometric redshift distributions by this method (Totani & Yoshii 2000, hereafter TY00). Here we briefly summarize the methods and the model of TY00.

The number density of galaxies is normalized at z=0 by the observed B band luminosity function (see Table 1 of TY00). Galaxies are classified into five morphological types of E/S0, Sab, Sbc, Scd, and Sdm, and their luminosity evolution is followed by luminosity evolution models of Arimoto & Yoshii (1987) and Arimoto, Yoshii, & Takahara (1992). These models are made to reproduce colors and chemical properties of local galaxies. Absorptions by interstellar dust and intergalactic HI clouds are taken into account. Possible number evolution of galaxies is considered by a phenomenological model in which the Schechter parameters of the luminosity function have a redshift dependence as $\phi^* \propto (1+z)^{\eta}$ and $L^* \propto (1+z)^{-\eta}$, i.e., luminosity density is conserved. The formation redshift z_F of galaxies is simply assumed to be 5 for all galaxies, but changing this parameter in a reasonable range ($z_F \sim$ 3–10) would hardly change the conclusion derived in this letter. (See Table 3 of TY00 for the summary of dependence of the count model on various parameters and systematic model uncertainties.)

The selection effects are calculated using simplified one-dimensional smooth-profile models and analytic estimates of the surface brightness thresholds. This is a good first approximation, although our calculation does not include a full simulation of the images and their noise properties with two-dimensional galaxy morphologies. The size of galaxies is estimated by the size-luminosity relation observed for local galaxies. The exponential and de Vaucouleurs' laws are assumed for the surface brightness profile of spiral and elliptical galaxies, respectively. The galaxy size is assumed to be constant except in the case of number evolution. We assume that the change of galaxy luminosity and size caused by number evolution obeys a scaling relation of $L \propto r^{\xi}$ during the merger processes with $\xi = 3$, and changing the value of ξ in a reasonable range of 2–4 hardly affects the count predictions, unless unrealistically strong number evolution is invoked (TY00). The possible intrinsic size evolution not induced by merging will be checked in §4. We calculate the isophotal size and isophotal magnitude for each model galaxy using the detection isophote applied in the HDF and SDF surveys, taking into account all the selection effects mentioned above. The galaxies meeting the detection criteria of the HDF or SDF are counted in the model galaxy counts, and then they are compared to the raw observed counts consistently as a function of isophotal magnitudes. In this way we find the best model to explain the observations with the selection effects properly taken into account.

3. RESULTS

TY00 found that a galaxy count model with a modest number evolution ($\eta = 1$) in a Λ-dominated flat universe with $(\Omega_0, \Omega_\Lambda, h) = (0.2, 0.8, 0.7)$ gives the best explanation not only for the observed counts but also the photometric redshift distribution of the HDF galaxies. This cosmological model is now the best favored by various cosmological observations. The number evolution of $\eta \sim 1$ is also consistent with the observational constraint on the merging fraction of galaxies at $z \lesssim 1$ (Le Févre et al. 2000). This model is referred to as the model A in the following.

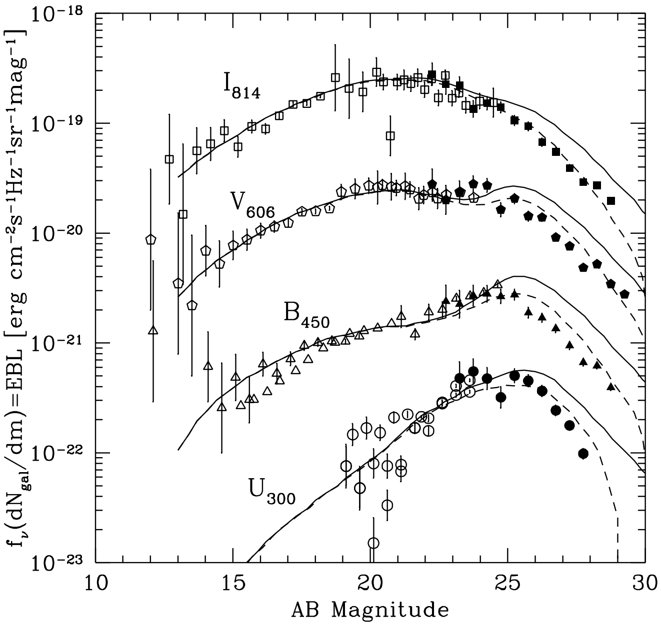

Fig. 1.— The contribution to EBL by galaxies in the four optical bands as functions of AB magnitudes. The filled symbols are the HDF data (in isophotal magnitudes), while the open symbols are ground-based data (see TY00 for references). The dashed lines are the predictions by the model A (see text) taking into account the selection effects under the observational conditions of HDF, fitting to the observed counts. The solid lines are the prediction by the same model, but without the selection effects in total magnitudes. For clarity, the data and model curves of the B_{450}, V_{606}, and I_{814} bands are multiplied by factors of $10^{0.5}$, $10^{1.3}$, and 10^2, respectively.

Figure 1 is the galaxy counts multiplied by flux, showing the contribution to EBL in the four passbands of the HDF as functions of AB magnitudes. The dashed lines are the predictions of the model A with the selection effects taken into account, and they exhibit a reasonable agreement with the observed counts in isophotal magnitudes. On the other hand, the solid line shows the model predictions in total magnitudes without the selection effects, i.e., the true galaxy counts. The excess of the solid lines over the dashed lines gives an estimate of the contribution by the missing galaxies to the EBL.

Figure 2 shows the contribution to EBL in the K band, including the latest data of the SDF. In Fig. 1 we have used the model A with number evolution of $\eta = 1$, but we found that this model seriously overpredicts the K counts, as shown by dotted lines in this figure. Rather, the K band counts can be fitted better by the pure luminosity evolution model with no number evolution ($\eta = 0$), when the same cosmological model as in the HDF is used (see Totani et al. 2001 in detail). The dashed line is this model with the selection effects, fitting well to the observed isophotal raw counts of the SDF (filled circles). The solid line is the prediction as a function of total magnitudes without any selection effects. For comparison, the SDF counts corrected for incompleteness assuming that all objects are point sources (Maihara et al. 2000) are also shown by the symbol $\odot$ as a function of total magnitudes. Here we assumed $K = K' - 0.1$.

This discrepancy between optical and NIR counts is probably coming from the limitation of the model assuming the same number evolution for all galaxy types. In the K band, elliptical or early type galaxies are more dominant in number compared with the optical bands. Therefore, this result may be understood if there is no or weaker number evolution for elliptical galaxies than that for other types. In addition, the giant and dwarf elliptical galaxies have been treated as distinct populations in Fig. 2, because it fits to the faintest K counts even better (see Totani et al. 2001 for the details). We refer to this model as the model B hereafter. We will use both of the two models in estimating the EBL, to see the model dependence of our calculation.

Now the contribution to EBL from galaxies missed in HDF and SDF can be estimated. We estimate the true galaxy counts by using the observed galaxy counts and models as follows:

$$N_{\rm true}(m) = \begin{cases} N_{\rm obs}(m)\left(\frac{N_{\rm m1}(m)}{N_{\rm m2}(m)}\right), & (m < m_{\rm lim}) \\ N_{\rm obs}(m_{\rm lim})\left(\frac{N_{\rm m1}(m)}{N_{\rm m2}(m_{\rm lim})}\right), & (m > m_{\rm lim}) \end{cases} \quad (1)$$

where $m_{\rm lim}$ is the faint limit of observed magnitude, $N_{\rm obs}$ is the observed counts, and $N_{\rm m1}$ and $N_{\rm m2}$ are the model counts without/with the selection effects, respectively. The estimate of EBL is simply given by the integration of $N_{\rm true}$. The ratio of the raw count integration to the true EBL from galactic light, which we call a resolution fraction, is shown in Table 1 both for the model A and B. The dependence on the two models is not significant. An overall trend is that the resolution fraction becomes greater with increasing wavelength, because the evolutionary effect of galaxies becomes less significant. Therefore, the

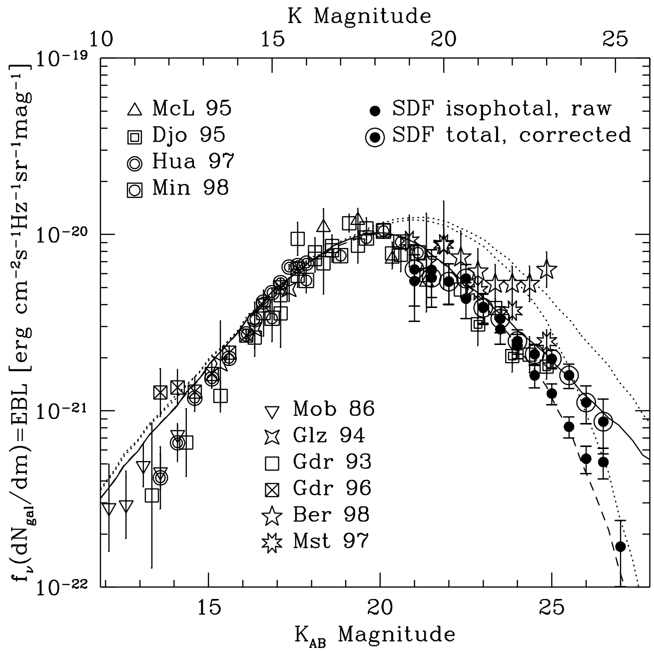

FIG. 2.— The same as Fig. 1, but for the K band. The filled circles are the raw SDF counts in isophotal magnitude, while the symbols $\odot$ are the counts in total magnitude which are corrected for incompleteness assuming point sources (Maihara et al. 2000). The dashed line is the prediction by the model B (see text) for which the selection effects under the observational conditions of SDF are taken into account, fitting to the raw counts. The solid line is the same prediction, but the selection effects are not included. The two dotted lines are the prediction by model A which is used in Fig. 1, with and without the selection effects. The other data are, McLeod et al. 1995 (McL95), Djorgovski et al. 1995 (Djo95), Huang et al. 1997 (Hua97), Minezaki et al. 1998 (Min98), Mobasher et al. 1986 (Mob86), Glazebrook et al. 1994 (Glz94), Gardner et al. 1993, 1996 (Gdr93, Gdr96), Bershady et al. 1998 (Ber98), and Moustakas et al. 1997 (Mst97).

best evidence that the bulk of EBL from galactic light has been resolved into discrete galaxies is given by the J and K counts of SDF; more than 80–90% of the NIR galactic light in the universe has been resolved.

4. CHECKING RELIABILITY OF OUR RESULTS

It should be noted that our estimate of the EBL flux from galaxies is essentially based on the observed counts, and the uncertainty concerning the model used here is relevant only to the contribution from missed galaxies. Given that this contribution of our best guess is not large compared with that from resolved counts, it is unlikely that the model uncertainty drastically changes the estimate of total EBL flux from normal galaxies.

To demonstrate the reliability of our analysis, we show a comparison of the observed isophotal size of galaxies and that predicted by the model used here, in Fig. 3, and this is a crucial check whether we have successfully modeled the systematic selection effects. In the above models we have assumed that the galaxy sizes do not evolve intrinsically with time except in the case of mergers. Fig. 3 shows that this no-size-evolution model is in reasonable agreement with the data, especially in the SDF. In order to check possible size evolution, we have also calculated the model prediction with a simple intrinsic size evolution (i.e., not caused by mergers), as $r_e \propto (1+z)^\zeta$ with $\zeta = -1$ and 1, where r_e is the effective radius of galaxies. The $\zeta = -1$ model is favored rather than the no-size-evolution model by the HDF galaxies, and hence we also show the resolution fraction of this case in Table 1. The resolution fraction becomes larger by the size evolution with $\zeta = -1$, because galaxies with smaller size are more easily detected when luminosity is fixed.

The discrepancy between HDF and SDF size distributions is probably coming from dependence of size evolution on galaxy types. There is no evidence for number or size evolution for elliptical galaxies, while later type galaxies seem to have evolved in size and number to some extent. In either case, there is no evidence that the size of high-z galaxies is intrinsically larger than local galaxies ($\zeta > 0$), and hence it is very unlikely that the size evolution effect drastically increases the contribution of missing galaxies to resolve the discrepancy between counts and EBL.

We have used the empirical mean luminosity-size relation of local galaxies in the calculation of galaxy sizes. However, there is considerable scatter along the mean relation, and the largest uncertainty in the estimate of the selection effects is probably coming from this scatter. We have calculated the resolution fraction using the size-luminosity relation shifted by $+1\sigma$ scatter in $\Delta(\log r_e)$ (see Fig. 3 of TY00), in the direction of larger size and hence more significant selection effects. The results are given in Table 1, and the resolution fraction in the B band could be as small as $\sim 60\%$ by this uncertainty, but that in the K band is still $\gtrsim 90\%$ (Table 1). The resolution fraction of SDF is less sensitive than HDF to the uncertainties about

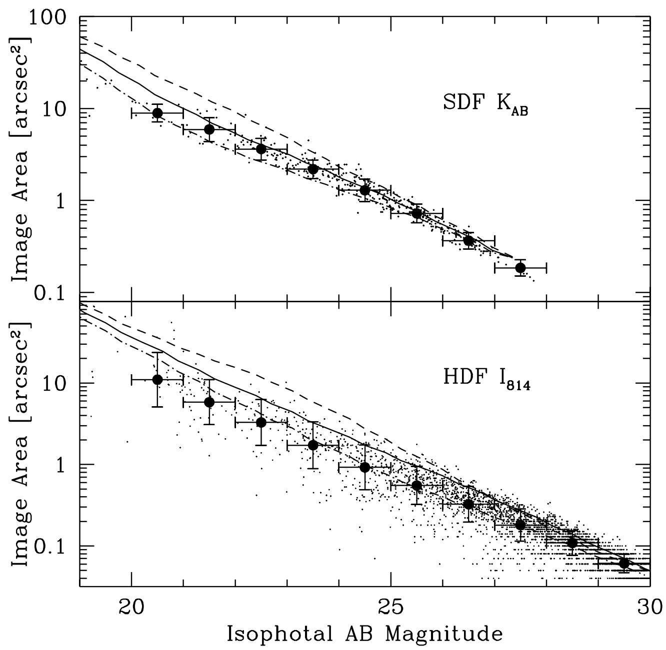

FIG. 3.— Magnitude-size relation for SDF and HDF galaxies. The size is estimated by the isophotal area of galaxies. The small dots are for individual galaxies, while the filled circles are mean size, with the vertical and horizontal error bars showing 1σ dispersion and the magnitude intervals, respectively. Three curves are the mean isophotal area predicted by the theoretical model (model A for HDF and model B for SDF, see text), for different size-evolutions of galaxies: $r_e \propto (1+z)^\zeta$ with $\zeta = 1$ (dashed), 0 (solid), and -1 (dot-dashed).

galaxy sizes, as can be seen in Table 1. This is because the seeing size is comparable or larger than the original galaxy sizes. In fact, the solid line in Fig. 2 is very close to the count data independently corrected assuming point sources ($\odot$), and this suggests that the extended nature of galaxies is not important at least in SDF. [Note that the situation is different for HDF in which the cosmological dimming is important (TY00), because of the better angular resolution than SDF.] This result further reduces the room of model uncertainties in our estimate of missing galactic light in the K band.

5. CONCLUSIONS

For the first time we presented a quantitative estimate of contribution to EBL from galaxies missed in deep surveys by various selection effects. The range of true EBL from galaxies of our best-guess is shown in Table 1, considering the range of resolution fractions of the four models and uncertainties in the raw integration of observed counts. Then the K band (2.2μm) EBL flux from all galaxies is unlikely to be larger than 10.2 nW m^{-2}sr^{-1}, but this is considerably smaller than the recent direct measurements of EBL in this band shown in Table 1.

Therefore, normal galaxies missed in deep surveys cannot reconcile the discrepancy between the count integration and diffuse EBL in optical and NIR bands. Unless there is crucial systematic error in the diffuse EBL measurements, there must be a very diffuse component of EBL which cannot be explained by known galaxy populations. If it is the case, the impact on galaxy formation and cosmology would be quite significant, and further study is required especially for more accurate measurements of diffuse EBL.

This work is partially based on the data corrected at the Subaru telescope, which is operated by the National Astronomical Observatory of Japan. We would like to thank T. Matsumoto for providing us with his data of diffuse EBL measurement.

Note Added.— After acceptance of this letter, we found two more reports for the J and K band EBL flux, by Write & Reese (2000) and Cambresy et al. (2001). These are added in the reference lists as well as in Table 1. Both are well consistent with the other diffuse EBL measurements, and it seems that the discrepancy between counts and diffuse EBL is even more severe in the J band than the K band.

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TABLE 1

EBL FLUX AND RESOLUTION FRACTION OF RESOLVED GALAXIES

Band (λ/Å)	U(3000)	B(4500)	V(6100)	I(8100)	J(12500)	K(22000)
	Simple Integration of Observed Galaxy Counts[a]					
Ref. 1	$(2.9^{+0.6}_{-0.4})^b$	$4.6^{+0.7}_{-0.5}$	$(6.7^{+1.3}_{-0.9})^b$	$8.0^{+1.6}_{-0.9}$	$(9.7^{+3.0}_{-1.9})^b$	$7.9^{+2.0}_{-1.2}$
This work	2.7 ± 0.3	4.4 ± 0.4	6.0 ± 0.6	8.1 ± 0.8	10.9 ± 1.1	8.3 ± 0.8
	Estimate of Resolution Fractions					
Model A[c]	0.78	0.78	0.87	0.90	0.97	0.93
Model B[c]	0.82	0.83	0.90	0.92	0.95	0.92
size evolution ($\zeta = -1$)[d]	0.81	0.92	0.93	0.96	0.94	0.96
$+1\sigma$ in size[d]	0.68	0.61	0.76	0.82	0.95	0.89
	Our Best-Guess EBL from All Normal Galaxies in the Universe[a]					
	2.9–4.4	4.3–7.9	5.8–8.9	7.6–10.9	10.1–12.8	7.8–10.2
	Measurements of Diffuse EBL[a]					
Ref. 2	12.0±5.7		$(14.9\pm4.4)^b$	17.6±4.8		
Ref. 3						22.4±6.0
Ref. 4					28.9±16.3	20.2±6.3
Ref. 5					60±15	29.3±5.4
Ref. 6						23.1±5.9
Ref. 7					54.0±16.8	27.8±6.7

[a] The EBL and count integration νI_ν in units of nW m^{-2} sr^{-1}.

[b] Estimated at slightly different wavelengths from ours (see original references).

[c] Model A: number evolution with $\eta = 1$. Model B: no number evolution with $\eta = 0$, and distinct treatment for giant and dwarf elliptical galaxies. (See text for detail.)

[d] Using models A and B for 3000-8100 and 12500–22000 Å bands, respectively.

References. — (1) Madau & Pozzetti (2000), (2) Bernstein et al. (2001), (3) Gorjian, Wright, & Chary (2000), (4) Wright (2001), (5) Matsumoto et al. (2000), (6) Wright & Reese (2000), and (7) Cambresy et al. (2001)